Simulation of Ground Level Enhancements and Forbush Decreases Using the *High Altitude Water Cherenkov Observatory (HAWC)* Scaler System

Olivia Enríquez Rivera, A. Lara and R. Caballero López
for the HAWC Collaboration
Instituto de Geofísica, UNAM
Mexico city

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Outline

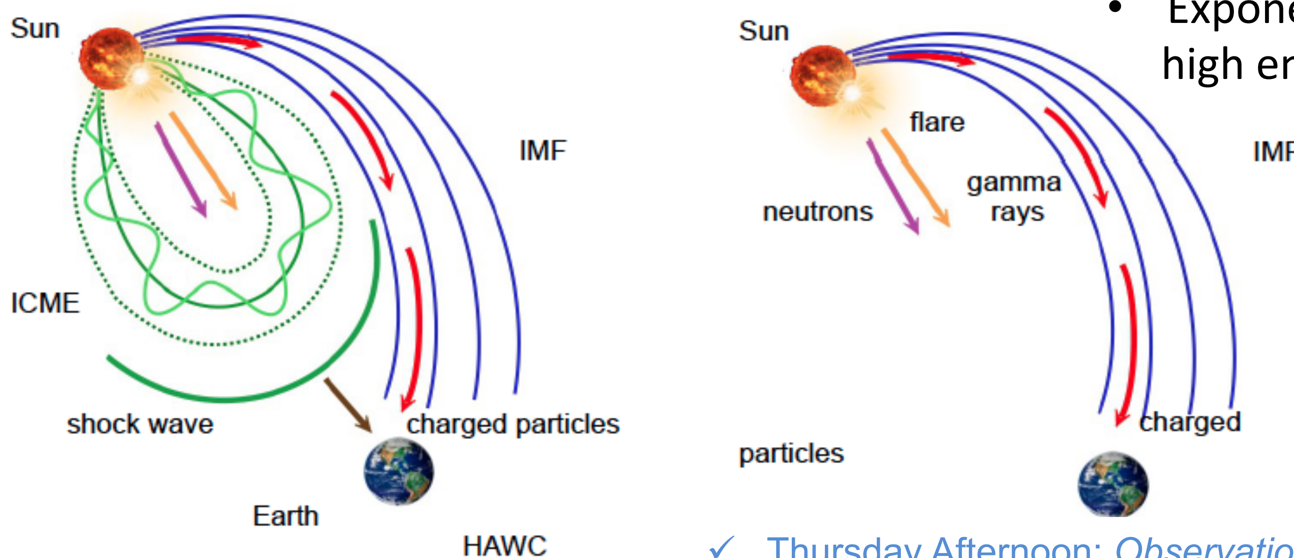
- ❑Motivation: GLE spectra with HAWC
- ❑Instrument: HAWC, Data Acquisition Systems
- ❑HAWC data: Sun shadow maps & Forbush dec.
- ❑Simulations: GLEs and Forbush decreases

Solar Transient Events & GCR energy spectra

- Galactic Cosmic Rays
- Forbush Decreases and GLEs (> 1 GeV)

GLEs:

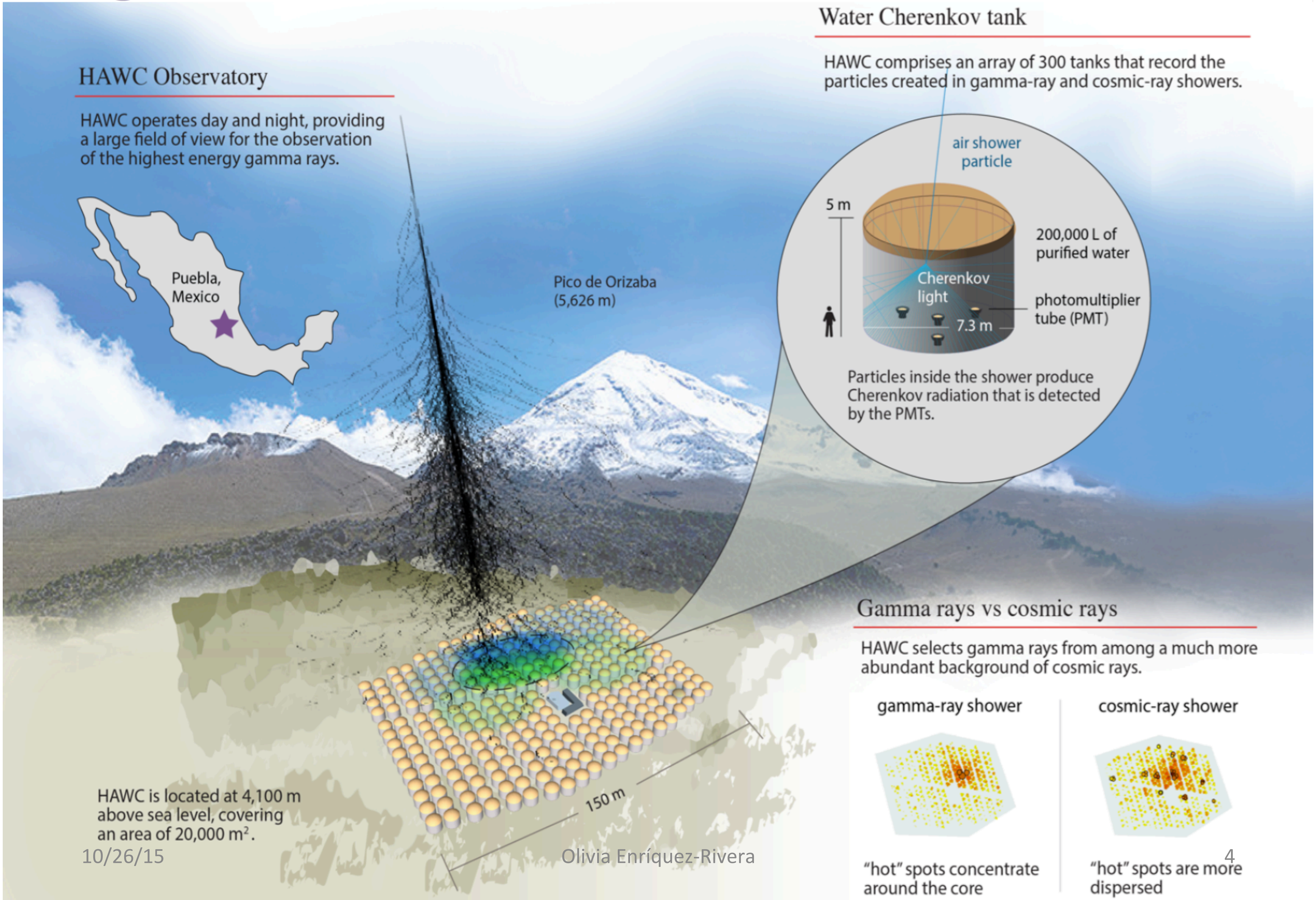
- Acceleration mechanisms ?
- Exponential rollover at high energies ?



✓ Thursday Afternoon: *Observation of Ground Level Enhancements",* Rogelio Caballero (invited talk).

- Neutron monitors: no angular sensitivity, different altitudes,geomagnetic and atmospheric cutoffs, anisotropic phase of GLE
- Non-standard GCR detectors: muon telescopes and air shower arrays (HAWC) able to resolve energy spectra at early phases.

High-Altitude Water Cherenkov



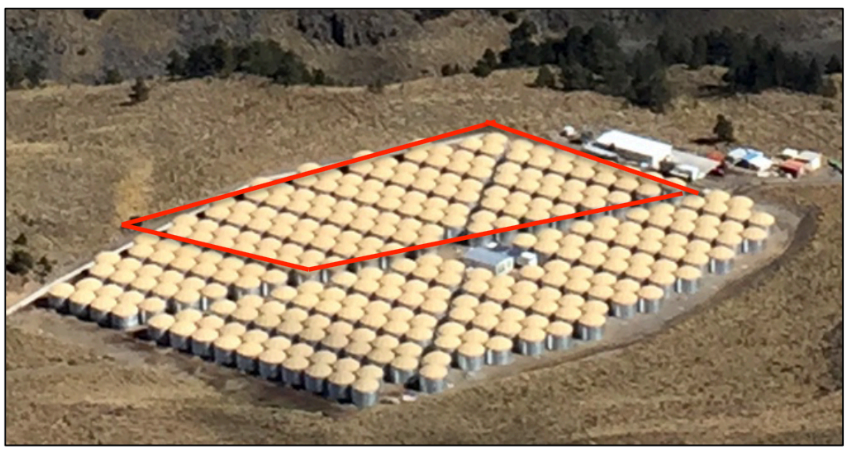
Data Acquisiton Systems

Main DAQ:

- Measures time over thresholds of PMT pulses
- Reconstruction of the air shower arrival direction
- and energy of the primary

Secondary DAQ (Scalers):

- PMT hits > ¼ photoelectron charge
- Particle detection below the energies of reconstructable showers.



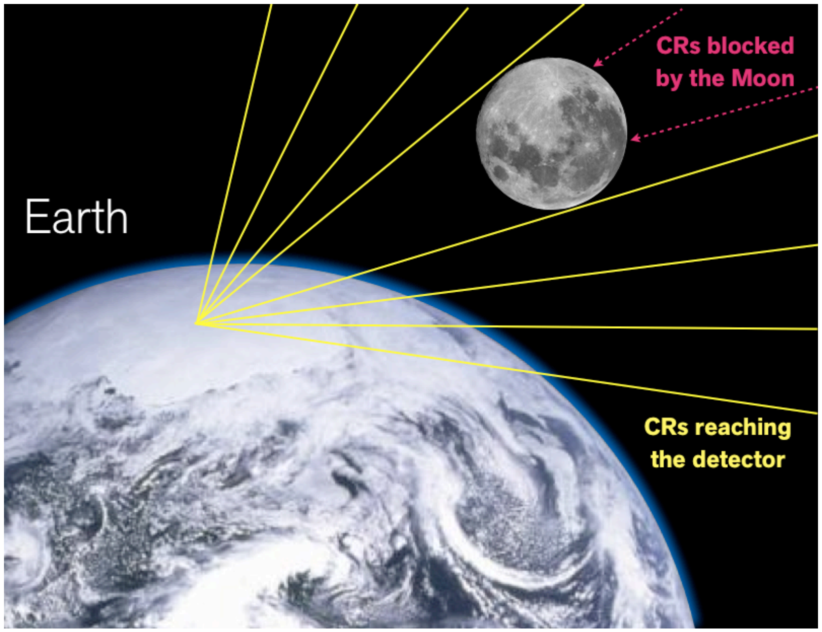
- HAWC 95-111 DATA (MAIN DAQ)

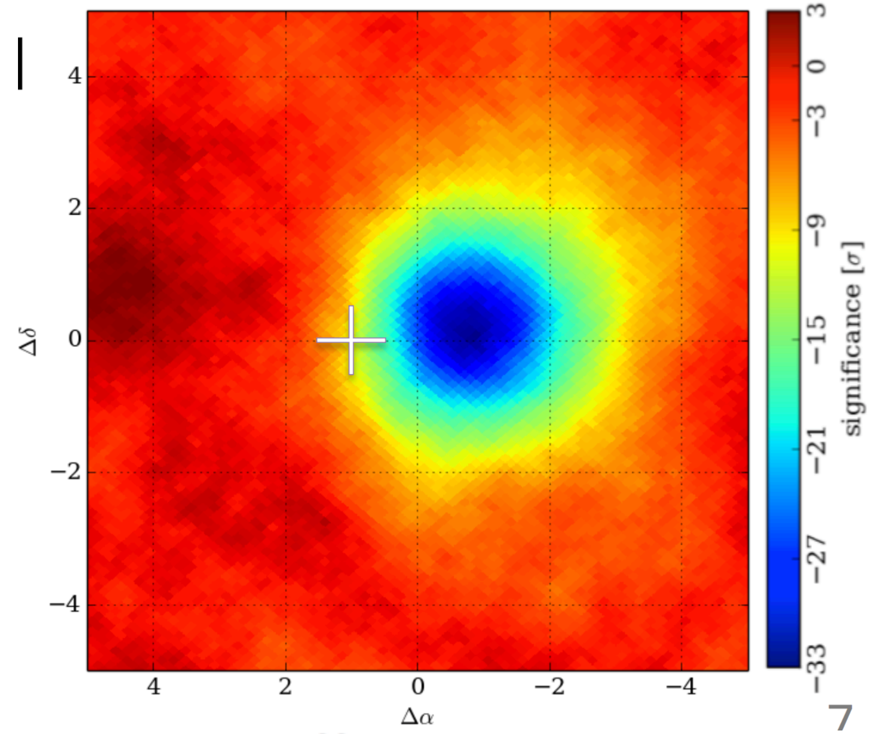
June 2013 to July 2014

181 days (4332.1 hr)

85.6 billion events

Main DAQ observations
Cosmic ray Moon shadow





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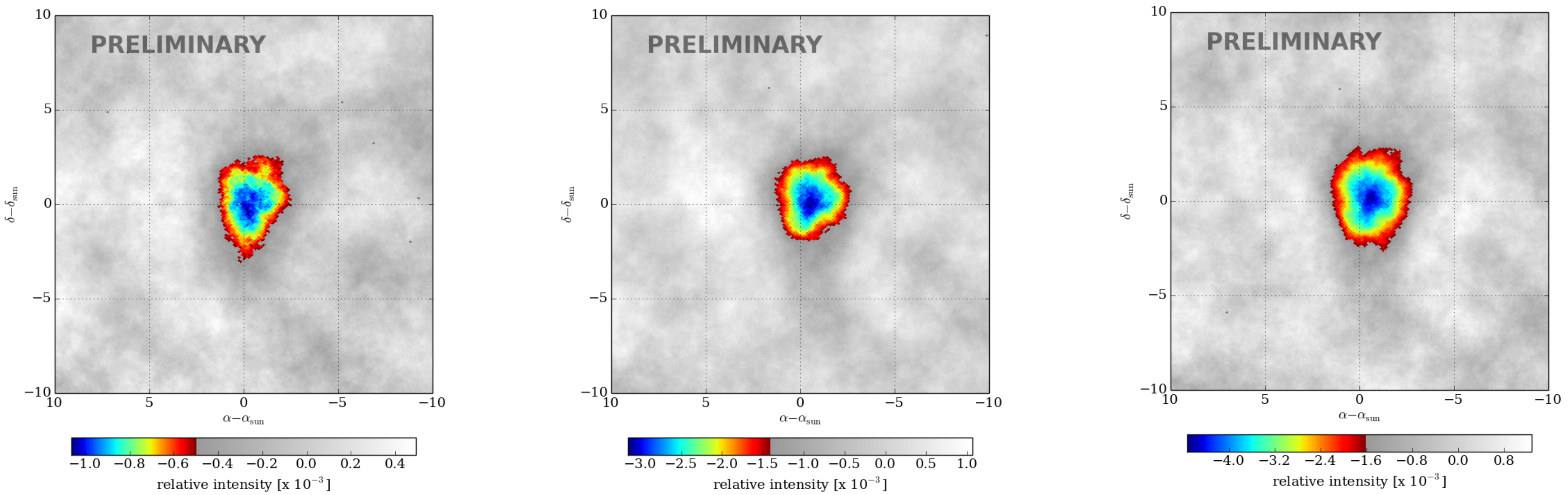
2 TeV median energy (0.9° offset)

$$\delta\theta \simeq 1.6^\circ \cdot Z \left(\frac{E}{\mathrm{TeV}}\right)^{-1}$$

1.2° angular resolution (1.2° width)

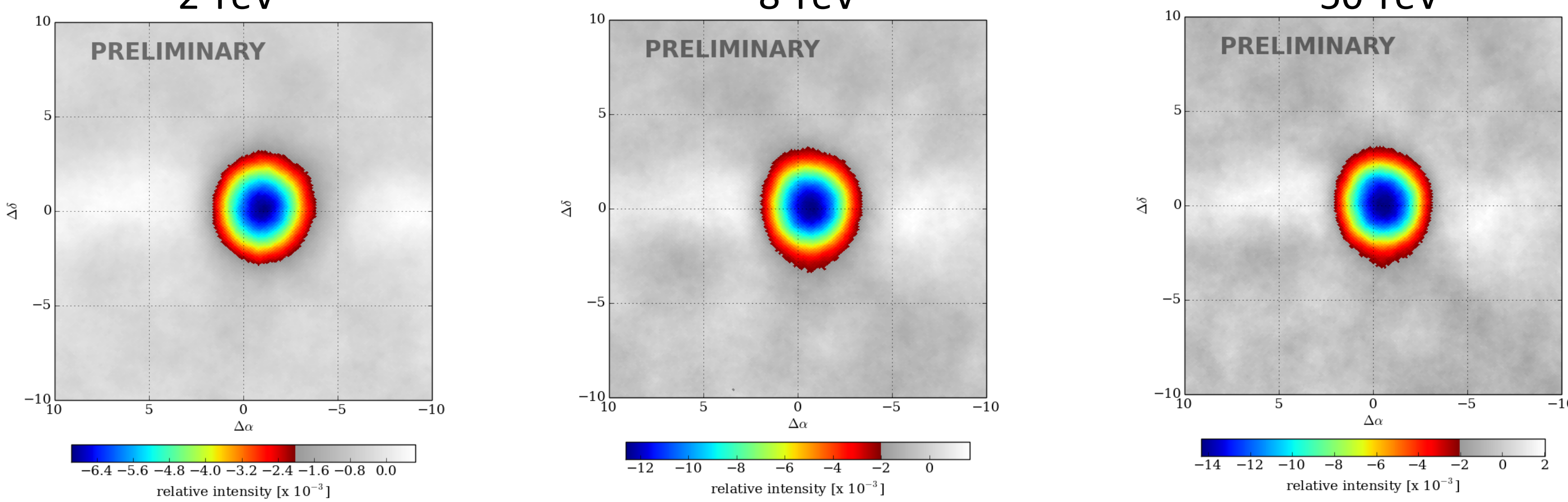
Cosmic ray Sun shadow



>30 nHit ~2 TeV

>72 nHit ~8 TeV

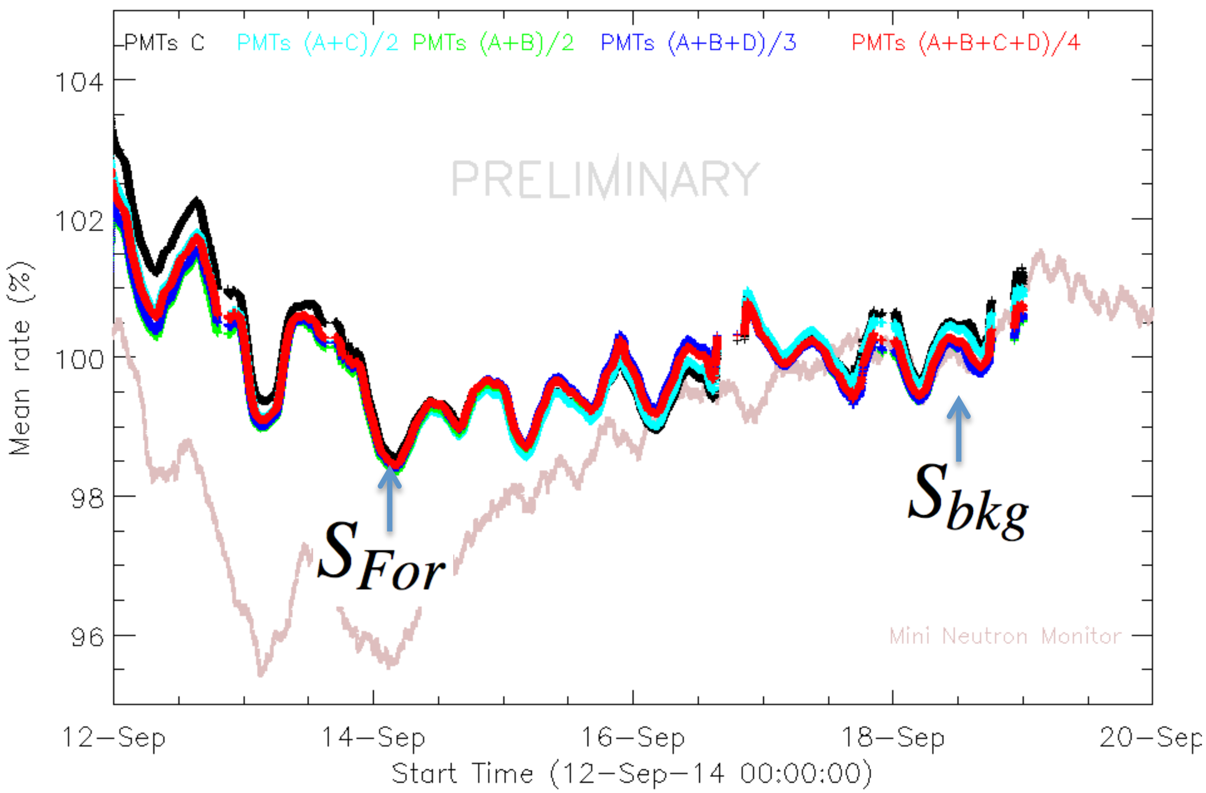
>109 nHit ~50 TeV



Scaler Observations
Forbush Decreases

- VAMOS (7 tanks)
- At present, 5 FDs

✓ Thursday Afternoon: "*Forbush decreases Observed by HAWC and their Interplanetary Drivers*", Alejandro Lara.

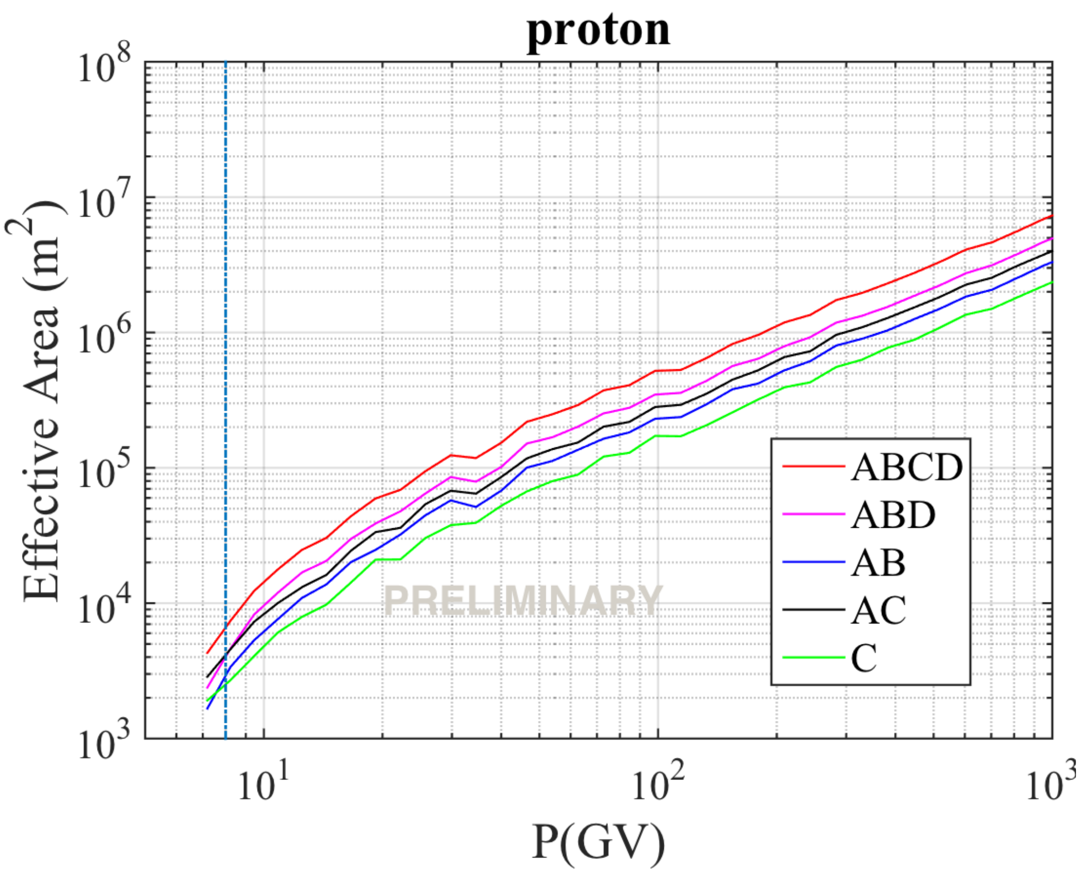


Double step FD

Colors: Mean relative count Rates using 5 PMT combinations

Light Brown: Mini NM at site

HAWC Scaler Simulation



1. CORSIKA
- 300 million primary protons
- 5 GeV-2000 TeV
- Zenith angles 0 – 75 deg

2. GEANT-4

3. Response of the electronics

4. Effective Area

- 300 tanks, different numbers of PMTs (different subarrays of the detector)
- Effective area scales with the number of PMTs

$$S(\theta) = \int_{P_{cut}}^{\infty} J(P,t) A_{Eff}(P,\theta) dP$$

Forbush Simulation

1. Calculation of FD min & bkg spectrum

- Obtain the force–field parameter $\Delta\phi$ and then *J(P)*
- Parameterization of *J(P)*: J_{gal} J_{For}

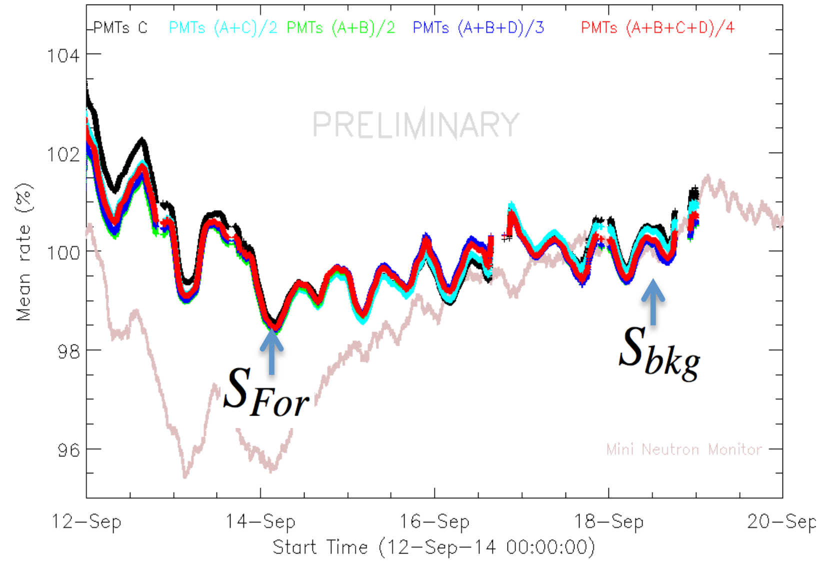
$$J(P) = J_0(P_0^a + P^a)^{(\gamma_1 - \gamma_2)/a} P^{\gamma_2}$$

2. Counting rate: S_{bkg} S_{For}

$$S(\theta) = \int_{P_{cut}}^{\infty} J(P,t) A_{Eff}(P,\theta) dP$$

3. Fractional decrement

$$(S_{bkg} - S_{For})/S_{bkg}$$



On September 14, 2014 HAWC registered a double-step FD

FD SIMULATION RESULTS

PMT CONFIG.	FD OBS %	FD SIM %	GLE SIM %
ABCD	2.85	2.10	44.4
ABD	2.83	2.00	41.1
AB	2.60	1.94	37.4
AC	2.80	2.10	43.4
C	2.91	2.08	42.8

- The simulated fractional decrease during the FD from Sep 14, 2014 is in agreement with HAWC scaler data for several PMT configs.

GLE Simulation

HAWC scaler response to GLE 42, September 29, 1989
GLE 42: 52 NMs (Mexico city, 8.15 GV) and 6 muon telescopes

1. Calculation of GLE max & bkg spectrum

- Estimation of $\Delta\phi$ to calculate bkg spectrum J_{gal}
- Parameterization of J_{gal} using $J(P) = J_0(P_0^a + P^a)^{(\gamma_1-\gamma_2)/a} P^{\gamma_2}$
- Obtain $J_s = J_0 E^{-\gamma}$ where $J_0 = 2.5 \cdot 10^5$ $\gamma = 4$.
  (delayed component of GLE 42, power law spectrum)
  From Vashenyuk et al., 2011; Moraal and Caballero-Lopez, 2014.

- Obtain $J_{GLE} = J_{gal} + J_s$

2. Counting rate

3. Fractional increment

GLE SIMULATION RESULTS

PMT CONFIG.	FD OBS %	FD SIM %	GLE SIM %
ABCD	2.85	2.10	44.4
ABD	2.83	2.00	41.1
AB	2.60	1.94	37.4
AC	2.80	2.10	43.4
C	2.91	2.08	42.8

← 44.2% in Mexico city!

- The simulated fractional increase of the GLE 42 reproduces the increase for the nearby Mexico city NM (44.4%)

CONCLUSIONS

- HAWC is an EAS array sensitive to gamma rays and cosmic rays of very high energies (~TeVs)
- HAWC scaler system is well-suited to detect cosmic ray particles of lower energy (solar transient events). HAWC has already observed several Forbush decreases.
- HAWC has a large effective area. We are exploring, with the aid of simualtions, the use of multiple data channels with differing energy thresholds capable of resolving proton spectra at early phases of energetic events. Milagro has proved to be successful using this technique independently and in conjunction with other NMs (T. Morgan, et al., 2015, in preparation).
- To achieve this, we still need to make improvements in our simulations.

Thanks!

Backup

spectrum	solar cycle	J_0	P_0(GV)	a	γ_1	γ_2	Rig. Range
march 1987 ($\Delta\phi = 0$ GV)	minimum	14000	0.96	1.5	-2.7	2.8	$0.7 < P < 10^4$
sept 1989 ($\Delta\phi = 0.55$ GV)	maximum	14000	3.1	1.7	-2.7	1.2	$0.7 < P < 10^4$
sept 2014 ($\Delta\phi = 0.23$ GV)	maximum	14000	1.3	1.44	-2.7	2.2	$0.7 < P < 10^4$
sept 14, 2014 (FD) ($\Delta\phi = 0.5$ GV)	maximum	14000	1.78	1.44	-2.7	1.8	$0.7 < P < 10^4$

Table 1: Parameters obtained to fit cosmic ray spectra used in this work with Eqt. 3.2. Units of J_0 are $primaries/m^2\ s\ sr\ GV$